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EFFECT OF EXIT TEMPERATURE SAMPLING DENSITY ON MEASURED COMBUSTOR PERFORMANCE

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16. Abstract

An analysis of combustor exit temperatures obtained with traversing thermocouple probes was made to indicate what the effect on computed combustor parameters would be if the number of sampling points was decreased. A total of 585 readings in an area of 2500 cm^2 were obtained with the traversing probes at the outlet of an annular combustor. The analysis indicates that a combustor temperature rise determined from approximately 150 of these readings would yield a sufficiently accurate value of combustion efficiency (within 1 percent in the case of combustors having reasonable outlet temperature uniformity). However, a reasonable measure of the combustor exit temperature pattern factor requires in excess of 400 thermocouple readings.

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SUMMARY

An analysis of combustor exit temperatures obtained with traversing thermocouple probes was made to indicate what the effect on computed combustor parameters would be if the number of sampling points was decreased. A total of 585 readings in an area of 2500 square centimeters were obtained with the traversing probes at the outlet of an annular combustor. The analysis indicates that a combustor temperature rise determined from approximately 150 of these readings would yield a sufficiently accurate value of combustion efficiency (within 1 percent in the case of combustors having reasonable outlet temperature uniformity). However, a reasonable measure of the combustor exit temperature pattern factor requires in excess of 400 thermocouple readings. The choice of the number of sampling points required to obtain good accuracy in the temperature rise and pattern factor was not greatly affected by the absolute value of temperature rise or pattern factor. It is concluded that the use of fixed thermocouple rakes that have a low sampling density should be avoided in preference to traversing thermocouple rakes.

INTRODUCTION

An accurate determination of a combustor average exit temperature is very dependent on the number of thermocouples used to attain that average. It is generally understood that a low number of temperature sampling points should not be expected to yield average temperatures with any great accuracy. What is generally not known, however, is how many sampling points are required to obtain values which will provide a sufficiently accurate average.

In addition to the average exit temperature, present day combustor performance is also rated by the exit temperature pattern factor. The pattern factor is a measure of the temperature pattern uniformity and requires a measurement of the hottest temperature occurring anywhere in the exhaust. The requirement to determine the highest temperature implies a relatively high density of thermocouple measurements in the combustor exhaust area. Here again, the necessary value of temperature sampling density is not known.

This report presents the results of a short study undertaken to determine what effect a variation in the sampling density has on the accuracy of the average exit temperature and the computed pattern factor.

PROCEDURE

The present full-scale annular combustor tests conducted at the Lewis Research Center use a five-point circumferential traversing temperature probe. Three such probes, described in references 1 and 2, are mounted on a rotating drum and data are recorded every 3°. A shield occupies one sampling position for each probe, so each probe surveys only 117° rather than 120° of circumference. Thus, a total of 585 thermocouple readings are taken for each determination of exit average temperature and pattern factor. The temperature readings are obtained with aspirated platinum-rhodium thermocouples. The thermocouples are given 8 seconds to reach temperature equilibrium before the data are recorded.

The exhaust sampling area of these combustors is 2500 square centimeters, and the sampling density is one thermocouple reading per 4.27 square centimeters. The data are mass weighted in computing the average exit temperature, using values of total pressure measured by five probes at the same location as the thermocouples.

The data can be treated in several ways to show the effect of a decrease in the sample density upon the average temperature and the pattern factor. This was done by taking the data in the several possible combinations that would be representative of the use of fixed thermocouple rakes. For example, with measurements obtained every 3° there are 10 ways of selecting 12 rakes (by selecting positions at 3°, 33°, 63°, etc. for one way; then 6°, 36°, 66°, etc. for the second; up through 10 possible initial positions). Note that this technique assumes regular spacing of the thermocouple rakes. Such regular spacing often is dictated by the physical dimensions of the combustor exit and the structural problems inherent in a design with irregular spacing. Similarly, there are five ways of placing 24 thermocouple rakes, three ways of placing 40 rakes, etc. The combinations used are listed in table I.

CALCULATIONS

The mass-weighted values of exit temperature chosen as representative of any particular thermocouple rake position were averaged to give the average exit temperature. This mass-weighted value is used in the calculation of the combustion efficiency and the pattern factor. The pattern factor was calculated by using equation (1):

$$\text{Pattern factor} = \frac{T_m - T_{av}}{T_{av} - T_{in}} \tag{1}$$

where T_m is the maximum nonmass-weighted temperature occurring anywhere in the exhaust, T_{av} is the average exit temperature, and T_{in} is the combustor inlet-air temperature.

The average temperature and the pattern factor were computed for each orientation of sampling rakes. The average temperature was that obtained by averageing only the mass-weighted temperature that would have been recorded by the chosen fixed rake array. The pattern factor is computed from the maximum temperature measured by the array, the computed average temperature, and the inlet-air temperature for that test. The deviation of the combustor temperature rise $T_{av} - T_{in}$ from the temperature rise as determined by 585 measurements is also computed. The assumed correct value of the temperature rise and pattern factor is that value computed from 585 measurements.

RESULTS AND DISCUSSION

Figure 1 presents typical results that have been obtained with a combustor when the temperature data were analyzed as explained previously. The exit average temperature was 1490 K, and the pattern factor was 0.25 for this combustor. Figure 1 shows the effect of the sampling density on the variation in determining the temperature rise and in the computed value of the pattern factor. As shown in the figure, the maximum value of the variation in temperature rise determination falls below ±1 percent when the number of readings is approximately 150, or one per 16.7 square centimeters. For the test conditions indicated in the figure, a ±1 percent deviation in combustor temperature rise causes a variation in combustion efficiency of ±1 percent. Such an accuracy is considered to be very good in the light of probable accuarcies in determining the airflow and fuel-flow rates. Thus, 150 sampling points would yield a sufficiently accurate measure of the overall exit temperature and combustion efficiency. However, a greater sampling density must be used if the pattern factor is to be determined with reasonable accuracy. The lower plot in figure 1 shows the pattern factor variation for the same data used in the upper plot. The curves represent the extreme limits of the computed values of pattern factor. For low values of the sampling density, where many different temperature rake configurations are possible, the median values truly represent the line of 50 percent probability. That is, any sampling configuration, randomly selected, has an equal probability that its computed pattern factor would lie either above or below the median line. Note that the computed values of pattern factor are generally below the true value. High values of pattern factor are observed in only a few cases where very few sampling points were used and a low value of average temperature was obtained.

Low values of the computed value of pattern factor are to be expected since the true pattern factor is dependent upon locating and measuring the maximum local temperature occurring anywhere in the exhaust. The liklihood of finding the maximum local temperature decreases as the sampling density decreases. From figure 1(b), a number of sampling points in excess of 425, one per 5.88 square centimeters, is required to obtain a value within 10 percent of the actual value. Because of the usual variability of combustor performance, a pattern factor determination within 10 percent is considered an acceptable accuracy.

The data presented in figure 1 were obtained with a combustor, described in reference 3, that has undergone extensive development to improve its pattern factor. Figure 2 shows data for a combustor which is in the early stages of development and has a high value of pattern factor. The exit average temperature is 1345 K, and the pattern factor is 0.85. The conclusions reached as to the minimum number of sampling points required are also borne out by an examination of figure 2. A number of temperature samples slightly in excess of 150 would probably determine the temperature rise with sufficient accuracy. A number of sampling points in excess of 370 would give a fair value of the pattern factor, with an absolute error of 0.05 or less.

CONCLUSIONS

The effect of exit temperature sampling density on measured combustor performance was studied. It is concluded from an analysis of a considerable number of exhaust temperature measurements that combustor temperature rise can be determined with good accuracy with 150 sampling points; one reading for each 16.7 square centimeters of exhaust area. A considerably greater number of temperature sampling points, 425 as a minimum, or one per 5.88 square centimeters, is required to determine the pattern factor within 10 percent in a combustor having reasonably low values of pattern factor. The use of fixed thermocouple rakes, with a low value of the sampling density, is to be avoided since the tendency is for an optimistic (low) value of pattern factor to be computed when the sampling density is low. Since these results were obtained on only one size of combustor, they may not be applicable for all combustor exhaust sizes. However, the trends are probably correct and suggest that a similar analysis be performed for other combustor sizes.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 2, 1971,
720-03.

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2. Wear, Jerrold D.; Perkins, Porter J.; and Schultz, Donald F.: Tests of a Full-Scale Annular Ram-Induction Combustor for a Mach 3 Cruise Turbojet Engine. NASA D-6041, 1970.
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TABLE I. - ASSUMED THERMOCOUPLE RAKE COMBINATIONS

Number of rakes	Total number of readings in 2500 sq cm	Spacing between rakes, deg	Sampling density, sq cm/reading	Number of combinations used
12	60	30	41.6	10
24	120	15	20.8	5
40	200	9	12.5	3
60	300	6	8.33	2
117	585	3	4.27	1

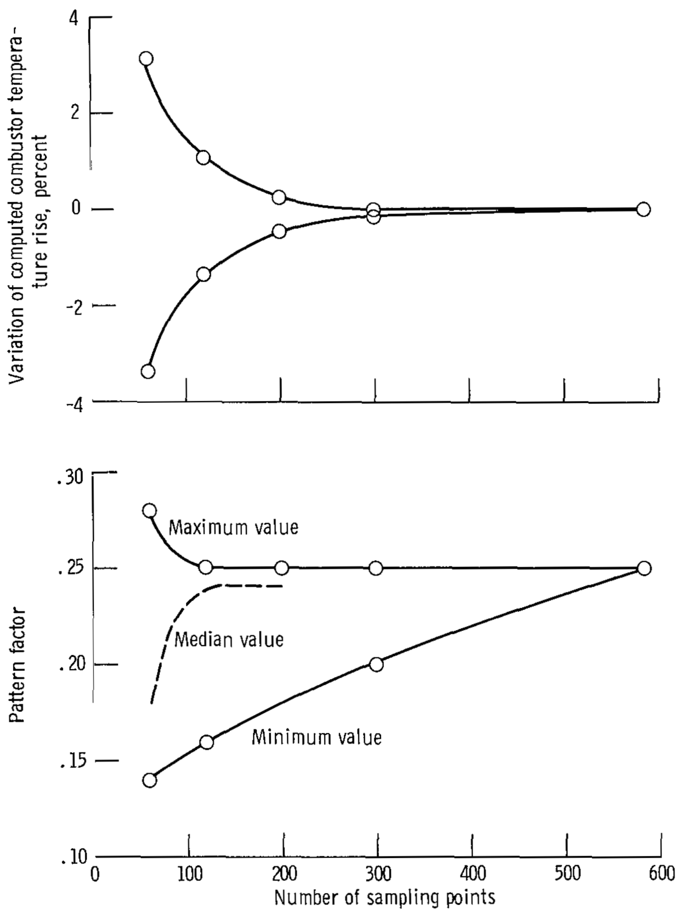

Figure 1. - Effect of number of sampling points on variation in computed temperature rise and pattern factor. Combustor exit average temperature, 1490 K; inlet-air temperature, 590 K.

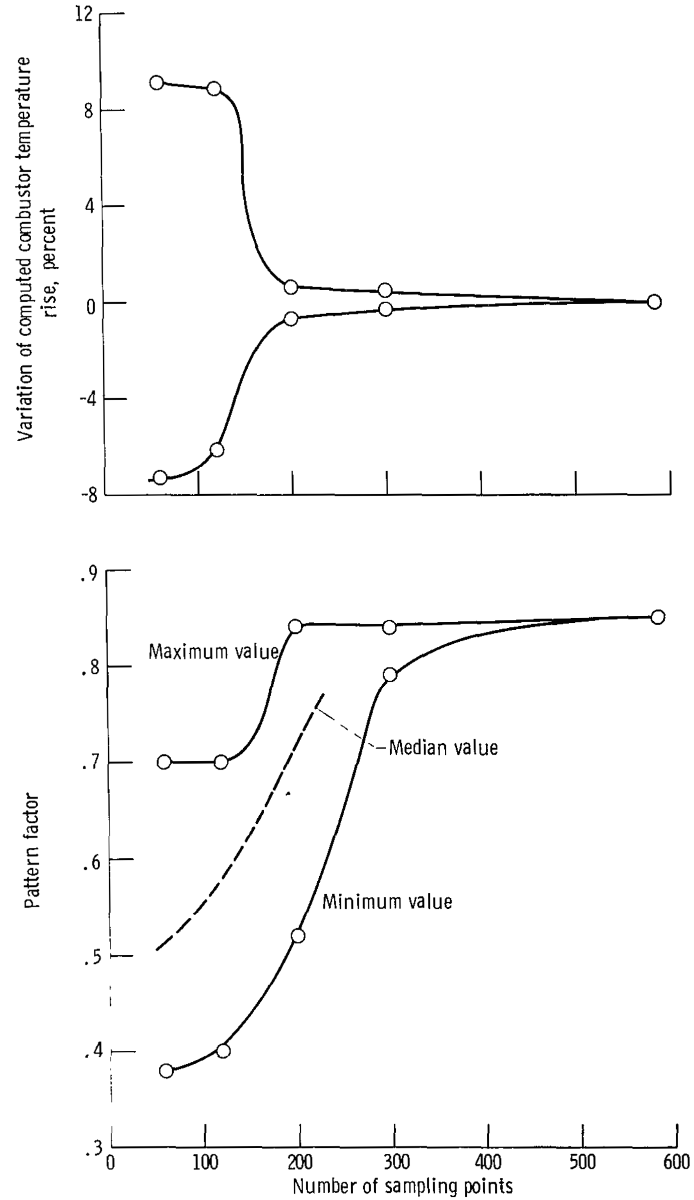

Figure 2. - Effect of number of sampling points on variation in computed combustor temperature rise and pattern factor. Combustor exit average temperature, 1345 K; inlet-air temperature, 585 K.

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